SYSTEM AND METHOD FOR NARROWING THE RANGE OF FREQUENCY UNCERTAINTY OF A DOPPLER SHIFTED SIGNAL

BACKGROUND OF THE INVENTION

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I. Field of the Invention

The present invention relates generally to wireless communication systems, and more specifically, to a system for narrowing the range of frequency uncertainty of a detected pilot signal with an unknown, but bounded amount of Doppler shift.

II. Description of the Related Art

A variety of multiple access communication systems and techniques have been developed for transferring information among a large number of system users. However, spread spectrum modulation techniques, such as code division multiple access (CDMA) spread spectrum techniques, provide significant advantages over other modulation schemes, especially when providing service for a large number of communication system users. The use of CDMA techniques in multiple access communication systems is disclosed in U. S. Patent No. 4,901,307, which issued February 13, 1990, entitled *"Spread Spectrum Multiple Access Communication System Using Satellite Or Terrestrial Repeaters,"* and U. S. Patent No. 5,691,974, which issued November 25, 1997, entitled *"Method And Apparatus For Using Full Spectrum Transmitted Power In A Spread Spectrum Communication System For Tracking Individual Recipient Phase Time And Energy,"* both of which are assigned to the assignee of the present invention, and incorporated herein by reference.

These patents disclose communication systems in which a large number of generally mobile or remote system users or subscriber units ("user terminals") employ at least one transceiver to communicate with other user terminals, or users of other connected systems, such as a public telephone switching network. Communication signals are transferred

either through satellite repeaters and gateways, or directly to terrestrial base stations (also sometimes referred to as cell-sites or cells).

In a modern satellite communications system, timing is critical. For example, such systems typically divide communications channels into "frames" where each frame is of a known duration. In order to optimize the use of such frames in transferring signals or data, the gateways or base stations and the user terminals must employ some method to ensure synchronization. Therefore, each user terminal is supplied with a device for providing a timing reference. An ideal time reference would supply the user terminal with a signal of a known frequency.

A local oscillator is often used to provide a timing reference in the user terminal. However, no local oscillator is perfect. Local oscillators are subject to frequency drift. When the frequency of the local oscillator drifts, synchronization is lost.

One approach to minimizing local oscillator frequency drift is to fabricate a more accurate local oscillator. However, such very stable local oscillators are very expensive to fabricate, and could unacceptably increase the cost of the user terminal.

Another approach, commonly used in cellular telephone systems, involves the use of a voltage controlled temperature compensated crystal oscillator (VTCXO). The output frequency of a VTCXO can be controlled by varying an input voltage to the VTCXO. The VTCXO is highly resistant to frequency drift caused by temperature changes.

In such a cellular telephone system, each user terminal is supplied with a VTCXO. Each user terminal monitors a pilot signal transmitted by a base station. The user terminal uses the frequency of the pilot signal as a timing reference to adjust the output frequency of the VTCXO by varying the input voltage applied to it. Such an approach can be used in a cellular telephone system because the relative velocities between the base stations and the user terminals are small.

However, in some satellite communication systems, such as low-earth orbit (LEO) satellite communication systems, the relative radial velocities between a satellite and a user terminal can be very large. This

large relative radial velocity imposes a large Doppler shift on the pilot signal transmitted by the LEO satellite, rendering this technique inaccurate and potentially unusable as a timing reference. When the satellite transmits a signal at frequency f_t, the received signal frequency f_r will be:

$$f_r = f_t \pm f_D \qquad (1)$$

$$f_D = f_t \bullet [V/c] \qquad (2)$$

where:

V = Velocity of transmitter relative to receiver;

c = speed of light in the appropriate medium; and

f_D = Doppler frequency shift.

If the satellite is moving toward the user terminal, the period of the electromagnetic wave is compressed and the [+] sign is used in the above equation. If the satellite is moving away from the user terminal, then the electromagnetic wave is elongated, and the [-] is used. The Doppler effect can be expressed as a Doppler ratio of [V/c] where V is the velocity of the transmitter relative to the receiver, and c is the speed of light in the appropriate medium. The magnitude of Doppler frequency shift is the Doppler ratio multiplied by f_t.

Doppler shifts are particularly acute in a LEO satellite system. For example, a typical LEO satellite can have a velocity of 7 km/sec relative to a user terminal. With a transmitter frequency of 2.5 GHz, this results in a Doppler ratio of 23 parts per million (or 23 ppm), and a Doppler frequency shift of 58 kHz (as calculated from equation 2 below).

Code Doppler error occurs whenever Doppler frequency shift is present and a digital data stream is being transmitted. Code Doppler error occurs because the transmitter is moving toward or away from the receiver causing the receiver bit rate to be increased or decreased relative to the transmitter bit rate. Code Doppler error is the Doppler ratio [V/c] times the transmitter bit rate. The resulting bit rate at the receiver is transmitter bit rate plus/minus code Doppler error where the [+] sign is used when the

transmitter is moving toward the receiver, and the [-] sign is used when the transmitter is moving away from the receiver. This relationship is shown by:

$$r_r = r_t \pm r_D \quad (3)$$

$$r_D = r_t \bullet [V/c] \quad (4)$$

where

r_r is the receiver bit rate,

r_t is the transmitter bit rate, and

r_D is the code Doppler error, and V and c are the same as in Equation 1 above.

Code Doppler error is especially harmful in a spread spectrum communications system because of its cumulative effect on pseudonoise (PN) generator synchronization. In a typical spread spectrum communications system, a set of preselected pseudonoise (PN) code sequences is used to modulate (i.e. "spread") the digital message over a predetermined spectral band prior to modulation of the carrier signal. For a spread spectrum receiver to properly "despread" the signal, the local PN generator chipping or chip rate (the rate at which chips are generated) must be time synchronized with the received signal chip rate. ["Chip" is a term of art that refers to a single PN code bit. Digital messages (voice, data, etc.) that have been spread with PN code chips are also sometimes referred to as comprising "chips," although "symbols" is preferred.] If the received signal chip rate is only a fraction of a Hz off, the clock error will accumulate over time causing the PN sequence to loose synchronization with the incoming bit stream. For example, a 0.1 Hz offset between the incoming chip rate and the local PN-generator results in a 0.1 chip per second timing error, which accumulates to 6 chips of timing error in 1 minute. That is, the received signal is shifted in time by 6 chips from where it should be in order for it to be properly despread by the appropriate PN-sequence. Spread spectrum receivers generally require code phase drift to be less than one-half of a chip

period to properly despread a signal. Greater than one chip of error produces useless information. Thus, it is important for code Doppler error to be monitored and corrected in spread spectrum receivers.

SUMMARY OF THE INVENTION

The present invention is directed toward a system and method of narrowing the range of frequency uncertainty of a detected pilot signal in a satellite communications system, where the pilot signal has an unknown, but bounded amount of Doppler shift. During detection of the pilot signal, information is gained to place the pilot signal within a frequency bin bounded by a lower and upper frequency. The invention shifts the detected pilot signal by a plurality of frequency hypotheses within the frequency bin, and then determines which hypothesis has the largest energy accumulation value. The hypothesis with the largest energy accumulation value is the closest hypothesis to the true center frequency of the pilot signal. Generally, the level of frequency discrimination that results is limited only by the number of frequency hypotheses tested between the lower and upper frequencies. However, when the pilot signal is a spread spectrum signal, there is tradeoff between the number of hypotheses tested and the accuracy of the energy accumulation value. In essence, code Doppler error causes a loss of time synchronization between the spread spectrum pilot signal and pseudonoise (PN) code sequence used to despread the pilot signal. The timing error increases with processing time (or number of hypotheses tested), and if uncorrected will lead to erroneous energy accumulation values for the latter frequency hypotheses.

The invention incorporates two refinements for correcting code Doppler timing error. First, the code Doppler error is estimated based on the final frequency of the frequency bin that is known to contain the detected pilot signal. The invention monitors the accumulation of the timing error over the plurality of frequency hypotheses and corrects the loss of synchronization before the timing error reaches a level that threatens accurate despreading of the pilot signal. The correction is done by advancing

or retarding the timing or chip rate of the PN sequence generation relative to its nominal rate.

The code Doppler error calculation is only an estimate since it is based on the assumption that the pilot signal is located at the upper frequency of the frequency bin. In reality, the pilot signal could be anywhere within the frequency bin. Thus, the above correction does not assure the necessary amount of synchronization needed to accurately despread the pilot signal over the plurality of frequency hypotheses. To further reduce the code Doppler error effect, the invention despreads two sets of the detected pilot signal in parallel during each frequency hypothesis. One pilot signal set is labeled "On-Time", and one pilot signal set is labeled "Late", where the Late set is sampled one-half of a chip period later in time relative to the On-Time sample set. By despreading two sets of pilot signal samples in parallel, where one set is shifted in time relative to the other, the invention achieves an overall reduction in synchronization timing error over the plurality of frequency hypotheses compared to that achieved when only one sample set is processed. This results because the Late sample set achieves minimum timing error at those hypotheses in the center of the pilot signal frequency bin, while the On-Time sample set achieves its minimum timing error for those hypotheses near the edges of the frequency bin.

BRIEF DESCRIPTION OF THE DRAWINGS

The features, objects, and advantages of the present invention will become more apparent from the detailed description set forth below when taken in conjunction with the drawings in which like reference characters identify correspondingly throughout and wherein:

FIG. **1** illustrates an exemplary wireless communication system in which the present invention is useful;

FIG. **2** illustrates an exemplary transceiver for use in a user terminal;

FIG. **3** is a flowchart depicting the operation of the present invention in narrowing the range of frequency uncertainty of a detected pilot signal according to a preferred embodiment of the invention;

FIG. **4** depicts a frequency bin bounded by f_i and f_f which is known to contain the Doppler shifted pilot signal;

FIG. **5** is a flowchart depicting the frequency translation of the detected pilot signal;

FIG. **6** is a flowchart depicting the despreading of the spread spectrum pilot signal;

FIG. **7** is a flowchart depicting the comparison of the energy accumulation value of the current frequency hypothesis with the maximal energy accumulation value from the foregoing frequency hypotheses;

FIG. **8** is a plot of code Doppler timing error vs. processing time. The plot depicts two embodiments of the invention. The solid lines depict the preferred embodiment where two pilot signal sample sets are processed and the code Doppler error estimate is based on the final frequency f_f of the FIG. **4** frequency bin. The dashed lines depict one sample set where the code Doppler estimate is based on the middle frequency of the FIG. **4** frequency bin;

FIG. **9** is a block diagram depicting an example implementation of a preferred embodiment of the present invention;

FIG. **10** is a block diagram depicting an example implementation of a preferred embodiment of despreader **915** depicted in FIG. **9**; and

FIG. **11** is a timing diagram depicting the PN generator enable signal **938**b sent by timing generator **936** as controlled by the code Doppler Correction accumulator **933**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

I. Introduction

The present invention is particularly suited for use in communications systems employing low earth orbit (LEO) satellites. However, as would be apparent to one skilled in the relevant art, the concept of the present invention can also be applied to satellite systems that

are not utilized for communications purposes. The invention is also applicable to satellite systems in which the satellites travel in non-LEO orbits, or to non-satellite based systems.

The preferred embodiment of the invention is discussed in detail below. While specific steps, configurations and arrangements are discussed, it should be understood that this is done for illustrative purposes only. A person skilled in the relevant art will recognize that other steps, configurations and arrangements can be used without departing from the spirit and scope of the present invention. The present invention could find use in a variety of wireless information and communication systems, including those intended for position determination, and satellite and terrestrial cellular telephone systems. A preferred application is in CDMA wireless spread spectrum communication systems for telephone service.

II. A Typical Satellite Communications System

An exemplary wireless communication system in which the present invention is useful is illustrated in FIG. **1**. It is contemplated that this communication system uses CDMA type communication signals, but this is not required by the present invention. In a portion of a communication system **100** illustrated in FIG. 1, one base station **112**, two satellites **116** and **118**, and two associated gateways or hubs **120** and **122** are shown for effecting communications with two remote user terminals **124** and **126**. Typically, the base stations and satellites/gateways are components of separate communication systems, referred to as being terrestrial- and satellite-based, although this is not necessary. The total number of base stations, gateways, and satellites in such systems depend on desired system capacity and other factors well understood in the art.

User terminals **124** and **126** each include a wireless communication device such as, but not limited to, a cellular telephone, a data transceiver, or a paging or position determination receiver, and can be hand-held or vehicle-mounted as desired. Here, the user terminals are illustrated as hand-held and vehicle-mounted telephones **124** and **126**, respectively.

However, it is also understood that the teachings of the invention are applicable to fixed units or units with fixed locations where remote wireless service is desired, including "indoor" as well as "open air" locations.

Generally, beams from satellites **116** and **118** cover different geographical areas in predefined patterns. Beams at different frequencies, also referred to as CDMA channels or "sub-beams," can be directed to overlap the same region. It is also readily understood by those skilled in the art that beam coverage or service areas for multiple satellites, or antenna patterns for multiple base stations, might be designed to overlap completely or partially in a given region depending on the communication system design and the type of service being offered, and whether space diversity is being achieved.

A variety of multi-satellite communication systems have been proposed with an exemplary system employing on the order of 48 or more satellites, traveling in eight different orbital planes in LEO orbits for servicing a large number of user terminals. However, those skilled in the art will readily understand how the teachings of the present invention are applicable to a variety of satellite system and gateway configurations, including other orbital distances and constellations. At the same time, the invention is equally applicable to terrestrial-based systems of various base station configurations.

In FIG. **1**, some possible signal paths are illustrated for communications being established between user terminals **124** and **126** and base station **112**, or through satellites **116** and **118**, with gateways **120** and **122**. The base station-user terminal communication links are illustrated by lines **130** and **132**. The satellite-user terminal communication links between satellites **116** and **118**, and user terminals **124** and **126** are illustrated by lines **140**, **142**, and **144**. The gateway-satellite communication links, between gateways **120** and **122** and satellites **116** and **118**, are illustrated by lines **146**, **148**, **150**, and **152**. Gateways **120** and **122**, and base station **112**, may be used as part of one or two-way communication systems or simply to transfer messages or data to user terminals **124** and **126**.

An exemplary transceiver **200** for use in a user terminal **106** is illustrated in FIG. 2. Transceiver **200** uses at least one antenna **210** for receiving communication signals, which are transferred to an analog receiver **214**, where they are downconverted, amplified, and digitized. A duplexer element **212** is typically used to allow the same antenna to serve both transmit and receive functions. However, some systems employ separate antennas for operating at different transmit and receive frequencies.

The digital communication signals output by analog receiver **214** are transferred to at least one digital data receiver **216A** and at least one searcher receiver **218**. Additional digital data receivers **216B-216N** can be used to obtain desired levels of signal diversity, depending on the acceptable level of unit complexity, as would be apparent to one skilled in the relevant art.

At least one user terminal control processor **220** is coupled to digital data receivers **216A-216N** and searcher receiver **218**. Control processor **220** provides, among other functions, basic signal processing, timing, power and handoff control or coordination, and selection of frequency used for signal carriers. Another basic control function often performed by control processor **220** is the selection or manipulation of pseudonoise (PN) code sequences or orthogonal functions to be used for processing communication signal waveforms. Signal processing by control processor **220** can include a determination of relative signal strength and computation of various related signal parameters. Such computations of signal parameters, such as timing and frequency may include the use of additional or separate dedicated circuitry to provide increased efficiency or speed in measurements or improved allocation of control processing resources.

The outputs of digital data receivers **216A-216N** are coupled to digital baseband circuitry **222** within the user terminal. User digital baseband circuitry **222** comprises processing and presentation elements used to transfer information to and from a user terminal user. That is, signal or data storage elements, such as transient or long term digital memory; input and output devices such as display screens, speakers, keypad terminals, and handsets; A/D elements, vocoders and other voice and analog signal processing elements; etc., all form parts of the user digital baseband circuitry

222 using elements well known in the art. If diversity signal processing is employed, user digital baseband circuitry 222 can comprise a diversity combiner and decoder. Some of these elements may also operate under the control of, or in communication with, control processor 220.

When voice or other data is prepared as an output message or communications signal originating with the user terminal, user digital baseband circuitry 222 is used to receive, store, process, and otherwise prepare the desired data for transmission. User digital baseband circuitry 222 provides this data to a transmit modulator 226 operating under the control of control processor 220. The output of transmit modulator 226 is transferred to a power controller 228 which provides output power control to a transmit power amplifier 230. Transmit power amplifier 230 upconverts and amplifies the baseband signal for final transmission from antenna 210.

User terminal 200 can employ precorrection element 234 in the transmission path to adjust the frequency of the outgoing signal. This can be done by using well known techniques of up- or down-conversion of the transmission waveform. In the alternative, precorrection element 232 can form part of a frequency selection or control mechanism for the analog up-conversion and modulation stage preformed within the transmit power amplifier 230.

Information or data corresponding to one or more measured signal parameters for received communication signals, or one or more shared resource signals, can be sent to the gateway using a variety of techniques known in the art. For example, the information can be transferred as a separate information signal or be appended to other messages prepared by user digital baseband circuitry 222. Alternatively, the information can be inserted as predetermined control bits by transmit modulator 226 or transmit power controller 228 under control of control processor 220.

Digital receivers 216A-N are configured with signal correlation elements to demodulate and track specific signals. Searcher receiver 218 is used to search for pilot signals, or other relatively fixed pattern strong signals, while data receivers 216A-N are used to demodulate other signals

associated with detected pilot signals. For purposes of determining signal strength, however, a data receiver **216** can be assigned to track the pilot signal after acquisition to accurately determine the ratio of signal chip energies to signal noise. Therefore, the outputs of these units can be monitored to determine the energy in or frequency of the pilot signal or other signals. Receivers **216** also employ frequency tracking elements that can be monitored to provide current frequency and timing information, to control processor **220** for signals being demodulated.

The pilot channel is simply a signal that is not modulated by data, and may use a repetitive unchanging pattern or non-varying frame structure type input (pattern). That is, the orthogonal function, here a Walsh code, used to form the channel for the pilot signal generally has a constant value, such as all 1's or 0's, or a well known repetitive pattern, such as a structured pattern of interspersed 1's and 0's. This effectively results in transmitting only the PN spreading codes applied from the PN code generator. In addition, a pilot signal is non-power controlled. That is, the pilot signal is typically transmitted at a preselected fixed power level, which is not varied so that accurate measurements of signal power are achieved by user terminals.

Control processor **220** uses such information to determine to what extent the received signals are offset from the oscillator frequency when scaled to the same frequency band, as appropriate. This and other information related to frequency errors and Doppler shifts, as discussed below, can be stored in a storage or memory element **236**, as desired.

III. Detailed Invention Description:

FIG. **3** is an operational flow diagram illustrating the operation of the present invention in performing a fine frequency search. The invention will be described in the environment of a spread spectrum satellite cellular communications system, where the satellites are in low earth orbit(LEO) and have large radial velocities relative to the user terminals. However, those skilled in the art will recognize how this approach can also be applied to

signals transferred by base stations without using satellites. That is, where there is sufficient signal source/receiver motion to generate Doppler frequency shifts of concern. For example, when using other types of moving repeaters or a fast moving vehicle such as a high speed train.

In a step **303**, a detected spread spectrum pilot signal is submitted for processing by searcher receiver **218**. The pilot signal is down-converted from the received RF band by analog receiver **214** to baseband where it is A/D converted. If the incoming signal frequency matches the receiver center frequency, then the signal carrier frequency is converted to DC at baseband. This is referred to as being centered around DC. However, the Doppler frequency shift inherent to low earth orbit(LEO) satellite communications (or a source/user terminal configuration with rapidly changing separation distances) shifts the incoming signal out of the receiver center band. The frequency spectrum of the resulting baseband signal is not centered at or about DC (0 Hz) because of the Doppler frequency shift, but has a positive or negative frequency shift. As always, code Doppler error accompanies the Doppler frequency shift.

During detection, searcher receiver **218** determines whether or not the pilot signal is within a preselected frequency range, commonly referred to as a frequency bin, bounded by f_i and f_f, as illustrated in FIG. **4**. F_{max} in FIG. **4** is the frequency of maximum possible Doppler shift that occurs when the system parameters are at their most extreme. That is, the frequency bin defined by f_i and f_f can slide between $-F_{max}$ and $+F_{max}$. Searcher receiver **218** determines where the boundaries of a frequency bin or search range are located, and the present invention determines which frequency hypothesis is closest to the center frequency of the detected pilot signal. Note that FIG. **4** represents the detected pilot signal as a discrete tone for illustration purposes only. In reality, the 3-dB bandwidth of a typical spread spectrum signal can be 500 kHz wide, which complicates the task of determining the center frequency.

In a step **306**, the code Doppler error is estimated based on f_f of FIG. **4**. This estimate will be used to periodically adjust the timing of the PN generator in step **312**, wherein the PN-generator is used to despread the pilot

signal. In step **309**, the frequency spectrum of the pilot signal is translated by the current frequency hypothesis. A frequency hypothesis is a discrete frequency within the FIG. **4** frequency bin. The term "hypothesis" is used because it is not known which one of the FIG. **4** frequencies is the closest to the center frequency of the pilot signal until all FIG. **4** frequencies have been processed. The value of the current frequency hypothesis is provided in step **327**. In one embodiment, the initial frequency hypothesis is f_i of FIG. **4**, a lower frequency, and the frequency hypotheses are incremented from f_i to f_f, an upper frequency. In an alternative embodiment, one could choose f_f as the initial hypothesis, and decrement each hypothesis.

In another alternative embodiment, a bisection algorithm is applied in which the full frequency range between f_i and f_f is first divided in half and each half is tested for pilot energy. The winning half is then divided in half again and the process repeated. This implementation is faster than a sequential search when the number of subdivisions, bins, gets larger, say on the order of sixteen or more, but is slightly more complicated to implement.

The translated pilot signal is then despread in step **312** by multiplying the pilot signal by the proper PN sequence. In step **315**, the despread signal samples are coherently accumulated over x-number of chips. In step **318**, the energy is measured for the accumulated signal samples. In step **321**, the energy measurements are accumulated over x-chips and 'm' of these coherent accumulations are used to produce an energy accumulation value (EAV) for the current frequency hypothesis. Therefore, an EAV consists of x times m chips of data.

The basic tradeoff in selecting x is that larger values are most efficient at collecting energy to make a good decision about whether an hypothesis is correct, but the size of x and the width of the frequency range being tested are inversely proportional. That is, the larger the value of x, the smaller the width of the frequency bin or range being tested. In order to avoid having very narrow bins and requiring a larger number of hypothesis to test, x is selected or adjusted to be a reasonable size. A value of x equal to 256 for the exemplary system being discussed provides the approximate frequency bandwidth desired, here about 3 kHz, in the subintervals being tested. If the

value of x is doubled to 512, the tests would only be able to "see" pilots in a 1.5 kHz interval, and twice as many hypotheses would have to be tested to cover the total frequency range.

The larger the value used for m, the more energy that is accumulated, and the better each hypothesis can be tested. The size of m is limited by the fact that if it is made too large, hypothesis testing takes too long and possible Doppler error near the end of the testing will be excessive. A preferred value for m is 27 in the exemplary system discussed above, because that value is about as large as is desirable before incurring or running into excessive accumulation of Doppler error. Therefore, in an exemplary embodiment, the number of accumulated chips x is set at 256 and the number of accumulations used to generate EAV is set at 27.

In step **324**, the EAV for the current frequency hypothesis is compared with a stored maximal EAV produced by the foregoing frequency hypotheses. If the stored maximal EAV is the larger, then nothing is changed, and the inventive process proceeds to step **327** where the frequency hypothesis is incremented. But, if the current frequency hypothesis EAV is greater than the prior maximal EAV, then the current frequency hypothesis EAV replaces the prior maximum EAV for comparison with EAVs produced by future frequency hypotheses. The initial stored maximal EAV value is selected to be, or set at, zero so that any subsequent measurement value used for comparison is automatically higher and becomes the stored value for subsequent hypothesis testing.

In step **327**, the frequency hypothesis is incremented, and steps **309** through **324** are repeated for the new frequency hypothesis. The loop is repeated for each of the plurality of frequency hypotheses, where the frequency hypothesis with the largest EAV is the closest to the true center frequency of the detected signal.

Generally, the level of frequency discrimination that results is limited only by the number of frequency hypotheses tested between f_i and f_f. However, when the pilot signal is a spread spectrum signal, there is tradeoff between the number of hypotheses tested and the accuracy of the energy accumulation value. In essence, code Doppler error causes a loss of time

synchronization between the spread spectrum pilot signal and pseudonoise (PN) code sequence used to despread the pilot signal samples. The timing error increases with processing time (and thus the number of hypotheses tested), and if not corrected will lead to erroneous energy accumulation values for those frequency hypotheses in the latter part of the FIG. **4** frequency bin. In one embodiment, the number of hypotheses is chosen such that the frequency uncertainty of the detected pilot signal is reduced from 23 kHz to 3 kHz.

FIG. **5** is an operational flow diagram illustrating one embodiment for implementing the present invention in step **309**. In step **503**, the detected pilot signal is received after the processing of from step **306**. In step **506**, the detected pilot signal is digitized by an analog-to-digital conversion to produce signal samples at eight times the chip rate (8xChip). The current frequency hypothesis waveform is synthesized in step **509**, based on the input from step **327**. In step **512**, the signal samples are rotated by the current frequency hypothesis waveform resulting in the translation of the pilot signal frequency spectrum. The translated pilot signal is then despread in step **306**.

The closer the translated pilot signal's frequency spectrum is to DC, the more effective the despreading operation will be in compressing the spread pilot signal, which will ultimately produce relatively large energy accumulation values in step **321**. FIG. **5** is but one embodiment of step **309**. An alternative embodiment would be to translate the pilot signal prior to the analog-to-digital conversion via well known analog mixing techniques.

To test a hypothesis that a received signal is centered at F_1, that signal is translated by negative F_1 (this translation being accomplished in the RF/IF and digital rotator translations all combined) and then test to see if energy is detected at DC. To test a negative Doppler hypothesis, the digital rotator is used to translate the baseband signal by a positive frequency offset. A positive offset centers a baseband signal at DC if the Doppler shift is negative, and provides a good energy measurement. If the Doppler shift is not negative, the positive offset does not center the baseband signal at DC but moves it farther from being centered, resulting in a poor energy

measurement. In a similar manner, a positive Doppler hypothesis is tested by using the digital rotator to translate the baseband signal by a negative frequency offset, to attempt to center the baseband signal. Therefore, circuits measuring energy are generally doing so at DC, with the rotator shifting different portions of the incoming signal spectrum into DC for these measurements.

FIG. **6** is an operational flow diagram illustrating one embodiment of step **312**, where the pilot signal is despread. In step **603**, the translated signal samples are received from step **309**. As discussed in FIG. **5**, in one embodiment, the pilot signal is sampled at eight times the chip rate (8xChip) during the A/D conversion, although those skilled in the art will understand that other rates can be employed within the teachings of the invention for other applications. In step **606**, the samples are decimated to produce two sets of samples at 2xChip rate. For discussion purposes, one set is labeled "On-Time" and the other set labeled "Late". The Late samples are created by sampling the pilot signal 1/2 chip, or 4 clock pulses, later than the On-Time sample set. The Late sample set is generated to take advantage of the decision to base the code Doppler estimate on f_f, the final frequency hypothesis in the FIG. **4** frequency bin. As will be explained later, this results in lower code Doppler timing error over the plurality of frequency hypotheses compared to that produced when only one sample set is processed and the code Doppler error estimate is based on the middle of the FIG. **4** frequency bin.

In step **609**, the invention monitors the code Doppler timing error that has accumulated between pilot signal samples and the PN sequence that despreads the pilot signal. In step **612**, the PN-sequence is advanced or retarded as necessary to correct the code Doppler timing error. In one embodiment, the timing of the PN-sequence is advanced or retarded in one-eighth chip increments, and the timing of the advance or retard is based on the code Doppler error estimate. In step **615**, the On-Time samples are multiplied by a complex PN-sequence to create in-phase (I) and quadrature (Q) despread samples of the On-Time pilot signal. In step **618**, the Late samples are multiplied by the complex PN-sequence to create I and Q

despread samples of the Late pilot signal. In step **621**, the On-Time I and Q samples and the Late I and Q samples are coherently accumulated over x-number of chips in step **315**.

FIG. **7** is an operational flow diagram illustrating one embodiment of step **324**, where the energy accumulation values (EAVs) for the current frequency hypothesis are compared with the maximal stored EAV from the plurality of foregoing frequency hypotheses. In step **703**, the EAVs from the On-Time and Late sample sets for the current frequency hypothesis are received from step **321**. In step **706**, the On-Time and Late EAVs are compared to the maximal stored EAV from the plurality of foregoing frequency hypotheses. If the maximal EAV is the largest of the three, then processing proceeds to step **715**. But if either the On-Time or the Late EAV is greater than the maximal stored EAV, then the method or process proceeds to steps **709** and **712**. In step **709**, the larger of the On-Time or Late EAVs replaces maximal stored EAV for comparison in future frequency hypotheses. In step **712**, the current frequency hypothesis value and its On-Time/Late status is stored, replacing the preceding winning frequency hypothesis. In step **715**, a determination is made as to whether or not the just processed frequency hypothesis is the last frequency hypothesis in the FIG. **4** frequency bin. If the answer is no, then the inventive process returns to step **327** to increment the frequency hypothesis value and repeat steps **309** - **324**. If the answer is yes, then the currently stored winning frequency hypothesis is the closest hypothesis to the center frequency of the detected pilot signal as shown in step **718**. The winning frequency hypothesis and its On-Time/Late status will be used during the demodulation of the message that follows the pilot signal.

IV. Code Doppler Error Correction

In one preferred embodiment, the invention implements two related refinements for correcting code Doppler error. The first is to estimate the code Doppler error based on f_f, the final frequency in the FIG. **4** frequency bin. This estimate is used to adjust the timing of the PN-generators to

correct any accumulated timing error. The second technique is for the invention to process two sets of pilot signal samples in steps **312** - **324**. One set of samples is labeled "On-Time", and one set is labeled "Late", where in one preferred embodiment, the Late sample set is generated by sampling the pilot signal one-half chip period, or 4 clock pulses when using 8x sampling, later in time relative to the On-Time samples. These refinements will be elaborated on below.

A. Code Doppler Error Estimate and PN-generator Timing Adjustment.

Code Doppler error occurs whenever frequency Doppler is present and a digital data bit stream is being transmitted. In one example application discussed earlier, a 7 km/sec closing velocity between the transmitter and receiver will result in a Doppler ratio of 23 parts per million (or 23 ppm), and a 58 kHz Doppler frequency shift for a 2.5 GHz transmitter frequency. If the transmitter data rate is 1.0 Mbps, then code Doppler error will be 23 bps. That is, the received bit rate is 23 bps faster than the transmitted bit rate. For effective de-spreading, it is desired to have less than one-half chip error between the detected signal and the PN sequence used to despread the signal. Thus, in this example, the receiver PN-generator should be set at a clock rate of 23 bps faster than the transmitter chip rate.

In the above discussion, the code Doppler error was easily rectified by simply increasing the clock rate of the PN-generator by 23 bps relative to the transmitter bit rate. This was based on a Doppler ratio of 23 ppm, which was calculated from the 58 kHz of known Doppler frequency shift. In the present invention, however, the amount of Doppler frequency shift is unknown. In fact, that is the purpose of the present invention, to find the center frequency of a detected pilot signal with a bounded, but unknown amount of Doppler frequency shift. Thus, in one embodiment, the code Doppler error is estimated in order to adjust the clock rate of the PN-generators that are used to despread the pilot signal in step **312** of present invention.

The code Doppler error estimate is calculated from equations (1) - (4), which are repeated here for convenience:

$$f_r = f_t \pm f_D \qquad (1)$$

$$f_D = f_t \bullet [V/c] \qquad (2)$$

$$r_r = r_t \pm r_D \qquad (3)$$

$$r_D = r_t \bullet [V/c] \qquad (4)$$

where

V = Velocity of transmitter relative to receiver

c = speed of light in the appropriate medium

As discussed earlier, searcher receiver **218** determined the pilot signal is within a frequency bin bounded by f_i and f_f as shown in FIG. **4**. For purposes of the code Doppler estimate only, the invention assumes the received pilot signal is at f_f. Using this assumption and Eq. 1 and Eq. 2, the Doppler ratio [V/c] can be calculated, since the transmitter frequency (f_t) is known. From the Doppler ratio, the code Doppler error (r_D) can be calculated from Eq. 4 since the transmitter chip rate (r_t) is known. The pilot signal chip rate (r_p), which is the same as r_t, can then be estimated using the relationship of Eq. 3, given a known transmitter chip rate (r_t) , where the "+" is used if the f_r is greater than f_t, and the "-" is used if f_r is less than f_t. With an estimate of the pilot signal chip rate (r_p), one embodiment of the invention keeps track of the accumulated timing error between the pilot signal samples and the PN sequence in step **609**, where the PN sequence is nominally generated at the transmitter chip rate. When the timing error reaches one-eighth of a chip, the invention advances or retards the PN generator timing to correct the accumulated timing error, as shown in step **612** of FIG. **6**.

B. On-Time and Late Sample Sets

As discussed above, the code Doppler error estimate is based on f_f for the frequency bin of FIG. **4**. This is counter-intuitive since the most obvious frequency to base the code Doppler error estimate would be in the middle of the FIG. **4** frequency bin, assuming one wanted to have the best chance to

minimize the difference between code Doppler estimated frequency and the unknown actual pilot signal frequency. However, it will be shown that an f_f based code Doppler estimate and the processing of two sample sets in parallel results in a lower timing error over the plurality of frequency hypotheses compared to that achieved with a single sample set, where the code Doppler error estimate is based on the middle of the frequency bin.

The basis of the code Doppler timing correction discussed in part 'A' above is the code Doppler error estimate. Since the estimate is based on the pilot signal being at f_f, timing error will still accumulate between the pilot signal and the PN generators, unless the pilot signal by chance happens to be centered at f_f. This timing error is best described by the relationship:

$$\text{Timing Error} = \int^{[T_s * k]} f_{err}(x)\, dx\ ; \qquad (5)$$

where

$f_{err}(x)$ = [actual pilot signal chip rate] - [PN generator chip rate] (6)

T_s = time to process 1 frequency hypothesis (7)

= [# of step 315 accumulations] • [# of step 321 accumulations] • T_C

T_c = chip duration (8)

FIG. 8 is a plot of Code Doppler timing error vs. invention processing time. The x-axis could also be labeled [number of frequency hypotheses] since the processing time increases with each additional frequency hypothesis. The total processing time is T_S • [number of frequency hypotheses]. The dashed line represents the timing error that occurs when the code Doppler estimate is based on the middle of the frequency bin, and only one pilot signal sample set is processed. The solid lines represent the timing error that occurs when the code Doppler estimate is based on f_f of FIG. 4, and two pilot signal sample sets are processed in parallel. One sample set is On-Time and one sample set is Late, where in one embodiment the Late set is sampled one-half a chip period, or 4 clock pulses, later than the On-Time sample set.

When viewing FIG. **8**, it must be remembered that the goal is to minimize the magnitude of the timing error over the plurality of frequency hypotheses. The On-Time and Late curves of FIG. **8** illustrate that using these hypotheses in tandem offers a lower magnitude of timing error than just the middle of the bin hypotheses, as shown by the Middle Bin curve. This is easily seen between hypotheses f_a and f_b, where the Late curve offers a lower timing error than the Middle Bin curve. For the hypotheses less than f_a and greater than f_b, where the Late curve timing error is approaching its maximum magnitude, the On-Time curve is approaching its minimum magnitude. Since the On-Time and Late sample sets are processed **in parallel**, only one of them at a particular frequency hypothesis needs to have a low timing error magnitude in order for the pilot signal to be successfully despread in step **315**.

In summary, one preferred embodiment of the invention utilizes two related, but distinct, refinements to alleviate the effects of code Doppler error. The first refinement is to calculate a code Doppler error estimate based on f_f of the FIG. **4** frequency bin. This estimate is used to advance or retard the PN-generators to correct timing error that accumulates during processing of the plurality of frequency hypotheses. The second refinement is for the invention to process two pilot signal sample sets in parallel instead of just one sample set. In one preferred embodiment, the Late sample set is delayed by one-half chip relative to the On-Time sample set. This, in conjunction with a code Doppler estimate based on the FIG. **4** final frequency (f_f), results in a lower overall timing error magnitude over the plurality of frequency hypotheses when compared with a scheme that processes only one pilot signal sample set.

In the above discussion, the Late sample set is delayed by 1/2 chip relative to the On-Time sample set. This is but one preferred embodiment. Other preferred embodiments may delay the Late sample set by some fraction of a chip other than 1/2 a chip period.

The above description is but one embodiment to reduce the effects of code Doppler error. An alternative embodiment would be to base the code Doppler estimate on the middle of the FIG. **4** frequency bin, and process

three pilot signal sample sets in parallel. The three sample sets would comprise: an On-Time sample set; an Early sample set where the pilot signal is sampled a fraction of a chip before the On-Time sample set; and a Late sample set where said pilot signal is sampled a fraction of a chip after the On-Time sample set. Of course, this embodiment requires more hardware than processing only two sample sets, which might be disadvantageous in some situations.

V. Block Diagram of Invention:

FIG. **9** is a block diagram illustrating one example embodiment of the present invention. In this embodiment, the system includes: analog-to-digital converter **903**, complex rotator **906**, direct digital synthesizer **909**, programmable frequency accumulator **912**, signal despreader **915**, coherent complex accumulator **918**, energy detector **921**, energy accumulator **924**, energy max-detector **927**, code Doppler correction accumulator **933**, system clock **936**, and timing generator **939**.

A pilot signal **901** with an unknown amount of Doppler shift is detected by searcher receiver **218** and submitted for processing. The searcher receiver **218** determines that the pilot signal **901** is within a frequency bin bounded by f_i and f_f as shown in FIG. **4**. In one embodiment, pilot signal **901** is a complex spread spectrum signal with both in-phase (I) **901a** and quadrature (Q) **901b** components. The pilot signal **901** has been downconverted from the appropriate RF transmission band by analog receiver **214**, but its frequency spectrum is not centered at DC because of the unknown amount of Doppler shift.

The pilot signal **901** is digitized by analog-to-digital(A/D) converter **903**, where in one embodiment samples are produced at eight times the chip rate (8xChip or 8x oversampling). (It is typical for those skilled in the art to refer to a spread signal digital bit as a "chip". The PN code or spreading bits output by the PN generator are also referred to as "chips".) A complex rotator **906** then translates the frequency spectrum of pilot signal **901** by the current frequency hypothesis **907**. The current hypothesis is synthesized by a

direct digital synthesizer (DDS) **909** to produce translated pilot signal **910**. Translated pilot signal **910** is complex with I and Q components **910a,b**. The programmable frequency accumulator **912** supplies DDS **909** with the current frequency hypothesis value **911.** The frequency accumulator **912** increments current hypothesis value **911** over the plurality of hypotheses to be tested. This is determined by the programmed inputs of initial frequency **912a**, final frequency **912b**, and number of hypotheses **912c**. The initial frequency and final frequency correspond to f_i and f_f of the FIG. **4** frequency bin. The use of complex rotator **906** to translate the pilot signal's spectrum **901** after A/D conversion is but one embodiment. An alternative embodiment would be to translate the pilot signal **901** prior to A/D conversion using well known analog mixing techniques.

Spread pilot signal **910** is despread in despreader **915** by combining, such as through multiplying, signal **910** by the proper PN code sequences. In one embodiment, the in-phase (I) pilot signal component **901a** is spread with a PN sequence during transmission that is statistically independent from that used to spread quadrature(Q) component **901b**. This embodiment offers an additional level of isolation between user terminals that share the same frequency channel, but have distinct PN codes. In order to despread pilot signal **910**, the **915** despreader multiplies or otherwise combines I and Q components **910a,b** by, or with, the identical respective PN sequences that were used to spread the components during transmission.

In one preferred embodiment of the despreader **915**, the pilot signal I and Q components **910a,b** are decimated from eight times the chip rate (8xChip) to 2xChip rate to produce two sets of samples for each I **910a** and Q **910b** component. One sample set is labeled "On-Time" and one sample set is labeled "Late", where the Late set is sampled one-half chip, or 4 clock pulses later than the "On-Time" sample set. Thus, the despreader **915** produces four sample sets, namely: On-Time I component **916a**; On-Time Q component **916b**; Late I component **917a**; and Late Q component **917b**. The processing of two sample sets in parallel results in a lower timing error over the plurality of frequency hypotheses compared to processing only one sample set. Also, the code Doppler estimate **933a** is used by the code Doppler

correction accumulator(CDCA) **933** to periodically adjust the timing phase between the despreader **915** PN generators and the pilot signal **910**.

FIG. **10** illustrates one preferred embodiment of despreader **915** which includes: divide-by-4 decimators **1003**a,b; samplers **1006**a,b,c,d; delay elements **1009**a,b; in-phase PN-generator **1012**; quadrature PN generator **1015**, and multipliers **1018**a,b,c,d. Pilot signal I and Q components **910**a,b are decimated by the divide-by-4 decimators **1003**a,b to produce I and Q signals **1004**a,b at 2xChip rate. I component **1004**a is sampled by samplers **1006**a,b to produce signals **1007**a,b where the **1007**a signal is labeled "On-Time" and the **1007**b signal is labeled "Late", where Late signal **1007**b is sampled after delay element **1009**a. In one embodiment, delay element **1009**a delays Late I component **1007**b by one-half chip period, or 4 clock pulses, relative to the On-Time I component **1007**a. I component signals **1007**a,b are multiplied by PN-sequence **1013** generated by in-phase PN generator **1012** to produce On-Time and Late in-phase despread signals **916**a, **917**a. The Q component **1004**b is processed similarly by: samplers **1006**c,d; delay element **1009**b; and quadrature PN-generator **1015**; where the only difference is that the PN-sequence produced by the quadrature PN generator **1015** is statistically independent from that generated by in-phase PN generator **1012**. Thus, despreader **915** produces four sample sets, namely: On-Time I component **916**a; On-Time Q component **916**b; Late I component **917**a; and Late Q component **917**b.

The On-Time I and Q components **916**a,b and Late I and Q components **917**a,b are coherently accumulated over x-chips by the complex accumulator **918** to produce On-Time I and Q accumulated components **919**a,b and Late I and Q accumulated components **920**a,b. Digital accumulators are well known by those skilled in the art. In one embodiment, the coherent accumulation is done over 256 chips, but other periods can be used. Longer accumulation periods produce a higher signal-to-noise ratio, but also allow code Doppler error effects to build up. These effects can reduce the effectiveness of PN sequence despreading in subsequent frequency hypotheses processing.

Energy Detector **921** measures the energy of On-Time components **919**a,b and Late components **920**a,b. The On-Time signal energy is measured by adding the squares of the I and Q components **919**a,b to produce On-Time energy samples **922**. Similarly, the Late signal energy is measured by adding the squares of the Late I and Q components **920**a,b to produce Late energy samples **923**. Energy accumulator **924** accumulates m energy measurements over a period of m times x-chips (x-chips per coherent accumulation times m accumulations) to produce an On-Time energy accumulation value (EAV) **925** and a Late energy accumulation value (EAV) **926**.

EAVs **925** and **926** are then sent to an energy max-detector **927** where they are compared with a maximal stored EAV **928**b from the plurality of foregoing frequency hypotheses. If maximal stored EAV **928**b is the largest of the three, then nothing is changed and the frequency accumulator **912** immediately increments frequency hypothesis value **911**. But if either of On-Time or Late EAVs **925**, **926** is greater than maximal stored EAV **928**b, then the larger of On-Time or Late EAVs **925**, **926** replaces maximal stored EAV **928**b for future frequency hypothesis comparisons. Also, current frequency hypothesis value **911** is stored as winning frequency hypothesis **928**a replacing the previous winning frequency hypothesis. The On-Time/Late status **928**c of the winning EAV is also noted and stored.

After the current EAV comparison is complete, programmable frequency accumulator **912** increments frequency hypothesis value **911** and the loop is repeated for the new frequency hypothesis. The loop is repeated over the plurality of frequency hypotheses between f_i and f_f , and the winning frequency hypothesis **928**a that is stored after all hypotheses are tested is the closest to the center frequency of the Doppler shifted pilot signal **901**. Winning frequency hypothesis **928**a and its On-Time/Late status **928**b are sent to digital data receivers **216**A-N for use in demodulation of signals, such as traffic channel or message signals.

The number of frequency hypotheses tested is controlled by the initial programming of frequency accumulator **912** through input **912**c. Obviously, the more hypotheses that are tested, the closer winning frequency hypothesis **928**a is to the pilot signal's true center frequency. However,

because of code Doppler error effects, there is a tradeoff between the number of hypotheses tested and the ability to accurately despread pilot signal **910**. In one embodiment, the number of frequency hypotheses is chosen so that the invention narrows the frequency uncertainty from 23 kHz to 3 kHz.

The programmable code Doppler correction accumulator (CDCA) **933** monitors the accumulated timing error between the pilot signal **910** samples and PN sequences **1013, 1016** that has built up because of code Doppler error. In one embodiment, when the timing error has reached 1/8 chip in size, the CDCA **933** issues an "advance" or "retard" signal **937** to the timing generator **936** to correct the accumulated timing error.

FIGS. **9, 10,** and **11** illustrate one embodiment of the code Doppler correction implemented by CDCA **933**. System clock **939** generates clock signal **940** at an 8xChip rate as shown by FIG. **11**. Timing generator **936** is a divide-by-8 circuit that receives clock signal **940** and provides enable signals **938**a,b, nominally at a 1xChip rate to despreader **915**, as shown in FIG. **11**. Signal **938**a enables samplers **1006**a,b,c,d and signal **938**b enables PN generators **1012, 1015**. This results in in-phase signals **1007**a,b and quadrature signals **1008**a,b being despread using multipliers **1018**a,b,c,d and the codes output from PN generators **1012** and **1015**.

CDCA **933** is a programmable accumulator that calculates and monitors the accumulated timing error over the plurality of frequency hypotheses based on the code Doppler error estimate **934**. When the accumulated timing error reaches one-eighth chip, CDCA **933** issues an "advance" or "retard" signal **937** to timing generator **936**. The advance/retard signal **937** causes the timing generator to send the PN generator enable signal **938**b one-eighth chip earlier or later than nominal, depending on what is desired to correct accumulated timing error between pilot signals **910**a,b and PN sequences **1013, 1016.** As discussed above, the frequency that CDCA **933** issues the advance/retard signal at is dependent upon code Doppler estimate **934**.

For example, if the chip rate in the transmission signal is on the order of 1.2288×10^6 chips per second, and there is a code Doppler estimate (error)

of 40 ppm, then accumulated Doppler error in 1 second is $(^{40}/_{10^6}) \bullet 1.2288 \times 10^6$ chips per second or about 49.152 chips/sec. When 8x sampling is used the number of advance or retard increments/decrements per second is determined by how many 1/8 chips occur per second. Therefore, an accumulated error of 49.152 chips/sec is 393.216 (1/8 chips)/sec and requires this many advance or retard signals per second to be issued during the plurality of frequency hypotheses testing to correct. Those skilled in the art will understand how to determine the number of advances and retard signals or increment/decrement commands that are appropriate for a given chip rate and sampling frequency, as well as the use of non-fractional values.

VI. Conclusion

The previous description of the preferred embodiments is provided to enable any person skilled in the art to make or use the present invention. While the invention has been particularly shown and described with reference to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention.

What we claims as our invention is: